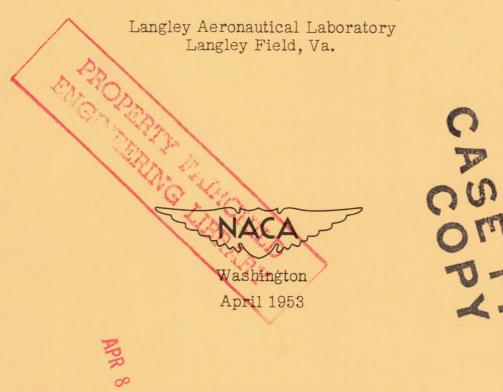
# NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2921

THE AERODYNAMIC DESIGN AND CALIBRATION OF AN ASYMMETRIC VARIABLE MACH NUMBER NOZZLE WITH A SLIDING BLOCK

FOR THE MACH NUMBER RANGE 1.27 TO 2.75

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# SUMMARY

A method of designing an asymmetric, fixed-geometry, variable Mach number nozzle has been developed by using the method of characteristics. A small nozzle conforming to the analytically determined ordinates was constructed and calibrated over a range of Mach numbers extending from 1.27 to 2.75. The results show the variation in Mach number to be  $\pm 0.02$  or less and in the flow direction to be  $\pm 0.2^{\circ}$  within the test section. The range of Mach numbers from 1.27 to 2.75 was obtained by translating the lower block in a straight line parallel to the test-section center line for a distance of 2.17 test-section heights.

### INTRODUCTION

Interest in the design and operation of variable Mach number nozzles has increased considerably recently because a number of large-scale supersonic research and development facilities are being planned or designed. A scheme which permits the Mach number in the test section to be changed by changing the relative position of two nozzle blocks, each of which has fixed geometry, was first investigated at the Ames Aeronautical Laboratory and is reported in reference 1. This type of variable Mach number nozzle has several features which make it most suitable for rapid supersonic testing of aircraft and aircraft components which operate over a moderately large Mach number range. The most important features are the following: With a nozzle of this type it is possible to change the test Mach number continuously during the test run. Low starting compression ratio is obtainable for this tunnel since it can be started while in the low Mach number position and later moved to a high Mach number setting. This latter advantage also eases the structural problem connected with models and model supports in that the starting loads can be reduced considerably. A simple variable second-minimum section can be combined with the translational movement of the block and low running pressure ratios obtained over the Mach number range. Since the Mach number is changed by a straight-line

<sup>&</sup>lt;sup>1</sup>Supersedes the recently declassified NACA RM L50L15, "The Aerodynamic Design and Calibration of an Asymmetric Variable Mach Number Nozzle With a Sliding Block For the Mach Number Range 1.27 to 2.75" by Paige B. Burbank and Robert W. Byrne, 1951.

translation of one part, the mechanism required is simple. The time-consuming process of changing nozzle blocks with the fixed-block, single Mach number design or of changing the nozzle contour with flexible walls is eliminated.

In the experimental investigation reported in reference 1, a nozzle was obtained which gives fairly constant velocity at the axis of the test section in the range of Mach numbers between 0.8 and 2.0. However, an appreciable variation of velocity in a direction normal to the stream was found with a consequent curvature of the streamlines for supersonic Mach numbers. The turning of the test-section stream, corresponding to the data presented in reference 1, was of the order of  $2^{\circ}$  in the high Mach number range.

In 1948 work was begun at the Langley Aeronautical Laboratory on a program of developing a variable Mach number nozzle of the asymmetric. fixed-geometry type. The general arrangement was similar to that considered in reference 1. The upper and lower blocks of the nozzle are of fixed geometry (not flexible); one block is translated in a straight line with respect to the other and in this way a continuous variation of test-section Mach number is obtained. The translation is in the direction parallel to the direction of the stream in the test section, and, therefore, the dimensions of the test section are maintained constant while the Mach number is changed. In contrast with the design procedure used in reference 1, however, the program described began with an analytical determination of the nozzle shape by using a characteristicnet construction in designing the nozzle over the design Mach number range and basic design criteria given later, which are due to Dr. Antonio Ferri of the Langley Laboratory. The first step was the determination of a method of obtaining a satisfactory characteristic net over the range of Mach numbers considered. After the principles had been established and shown to give satisfactory nozzle designs, various methods of application, together with experimental investigations, were initiated at both the Ames and Langley Laboratories.

This paper presents the basic design method and experimental results of a calibration of a nozzle which was constructed to conform to the analytically determined ordinates. The range of Mach numbers over which the nozzle was calibrated extended from 1.27 to 2.75.

## SYMBOLS

 $h_{\min}$  height of first minimum

h height of test section

d longitudinal positioning dimension for relative block positions

M Mach number

x,y coordinates of the blocks, in. (Reference axis is given in fig. 5)

# Subscripts:

L lower block

U upper block

# NOZZLE DESIGN

A Mach number range extending from 1.7 to 2.6 was selected as being representative of a range which would be of most immediate interest. The actual Mach numbers were 1.71 and 2.63, which were selected to avoid interpolation in existing supersonic-flow tables. It was first assumed and later checked analytically that, if a nozzle shape giving uniform flow in the test section could be determined for these two limits of the Mach number range, good flow could be expected at the intermediate Mach numbers and also for a limited range of Mach numbers above and below the design range.

Three design criteria were set up to be followed throughout the design: the nozzle contour was to have the second derivative of the same sign (without inflection points) in the supersonic-flow region; the variation of the first derivative of the nozzle contour should be continuous and smooth throughout the nozzle length; and no compression waves were to be used in the characteristic design of the nozzles. The nozzle contour was to be designed without inflection points in order to eliminate flow discontinuities which, as will be apparent from the following discussion, are difficult to handle in the characteristic-net construction used in the nozzle design. The necessity of introducing compression waves into the characteristic net is thereby avoided and the third design criterion is partially satisfied. It was desired to make the first derivative of the nozzle contour continuous and smooth so that a continuous variation of the flow phenomena could be expected over the Mach number range when one block is translated with respect to the other. This continuous variation of flow properties would also tend to insure uniform flow in the test section. The third criterion of not introducing compression waves into the net was chosen because compression waves tend to produce local thickening of the boundary layer and because these compression waves tend to collect and form a shock wave as they travel downstream.

In order to start the characteristic-net construction for the method presented, the shape of the sonic line must first be determined. In order to simplify the net construction it was decided that the subsonic entrance section should be designed in such a manner that the sonic line would be straight and perpendicular to the wall at the firstminimum section. The analysis presented in reference 2 and experimental results of reference 3 show that, if the nozzle walls in the vicinity of the minimum section are parallel and have zero curvature and the converging subsonic section approaching this region is very gradual, a straight sonic line can be obtained. The subsonic portion of the nozzle and the minimum section were designed to satisfy these conditions throughout the Mach number range and a straight sonic line was used in the characteristic-net construction; thus, the shape of the sonic line as a parameter in the nozzle design was eliminated. Since one block was to remain fixed and the Mach number to be varied by translating the other block in a straight line, the position of the sonic line on one block had to be kept fixed, while the sonic-line position on the other block moved along a portion of the surface which, therefore, had to be straight.

The details of the design procedure are described by presenting it as it was applied to the particular problem of designing a nozzle for the previously mentioned Mach number range. The method can, of course, be applied to other Mach number ranges close to the one selected in this paper.

The first step in analytically determining the shape of the nozzle was to design a nozzle shape which would satisfy the conditions of uniform flow in the test section at the two design Mach numbers of 1.71 and 2.63. Since the amount of flow turning required to obtain a Mach number of 1.71 was reasonably small (180), it was desirable to construct a characteristics net for this Mach number which was free of reflected waves. This procedure simplified the net construction and, as will be seen later, permitted a more accurate determination of the nozzle contour and kept the relative movement of the blocks to a minimum. Since the Mach number 1.71 net was to have 180 of turning to obtain the condition of no reflected waves and since the same nozzle shape had to develop a uniform flow at a Mach number of 2.63 (equivalent to 42° of turning) by simple translation in a straight line of one of the blocks, the net resulting from a Mach number 2.63 setting of the blocks would require 24° of flow expansion to be obtained by reflected expansions in the characteristic net for the higher Mach number. The procedure then was to design first the part of the 2.63 nozzle near the first-minimum section. For a first approximation to the nozzle shape, a characteristic net was constructed graphically for both Mach numbers with 20 expansion lines. The upper surface of the nozzle was maintained straight (A-B, fig. 1(a)) until a 240 difference in required expansion between the Mach numbers of 1.71 and 2.63 was made up by reflected waves. With

a 2° net, six reflections were required to make up the differences in flow expansion required. (See fig. 1(a).) The lower-nozzle surface from point C to point D is used to create enough expansion waves for the required number of reflections in the region A-B on the upper surface. The initial selection of point spacing of the expansion waves from C-D is arbitrary; however, considerations of over-all nozzle length and the criterion of smooth changes in curvature make it desirable to limit the point spacing to small intervals of nearly uniformly changing length from the minimum to the test section.

After the attainment of the required number of expansions in the region A-B, the upper-surface design was continued to point E which was the first point at which the upper surface had to curve in order to cancel an expansion wave. When point E was reached on the upper surface, the design of the net for the Mach number 2.63 nozzle was temporarily stopped. The first part of the lower surface (C-D) was then moved along a line inclined at an angle of 18° with respect to the straight line (A-B) on the first part of the upper block until the first 20 expansion line for M = 1.71 from point C hit the upper surface at the point E. (See fig. 1(b).) In figure 1, the positions of the two Mach number settings are shown removed from each other for clarity. Expansion lines were then drawn (fig. 1(b)) from each of the points from C to D to the upper surface where they were canceled by curvature of the upper surface. Points of curvature for the upper surface were, therefore, established between the points E and F. The design of the Mach number 1.71 net was then stopped and the construction of the Mach number 2.63 net resumed. The curvature just determined from points E to F was placed in its proper position in the Mach number 2.63 net (fig. 1(c)). From the newly determined points of curvature between E and F, expansion lines were drawn with slopes suitable for the Mach number 2.63 net, down backwards to the lower nozzle surface. Some of these expansion lines, in addition to having to pass through the points between E and F determined from the Mach number 1.71 net construction (fig. 1(b)), had also to agree with the lines originating in the region C-D previously drawn for the M = 2.63net (fig. 1(a)). The lines which did not have to meet these requirements fell in the region D-G and determined a new portion of the lower surface contour (fig. 1(c)). For this particular example, expansion lines which fell in the region D-G could either be designed to originate in this region or designed as reflected waves in this region. The final choice in the design in this region was dictated by meeting the conditions set up in the design of the first set of expansion lines in figure 1(a). A cut-and-try process was necessary in order to make the M = 1.71and M = 2.63 contours so far determined agree. This process consisted in adjusting the locations of the points of expansion in the two nets. The construction of the M = 2.63 net was temporarily stopped again and the newly determined portion of the lower surface D-G was then moved to its proper location on the Mach number 1.71 net (fig. 1(d)) and the shape of the upper surface from F to H was determined in the same

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manner as the shape from E to F was determined in figure l(b). A new portion of the upper surface was obtained (F-H) and the design of the Mach number 1.71 net was stopped and the design of the Mach number 2.63 net resumed. The portion of the upper surface (F-H) was then placed in its proper position on the Mach number 2.63 net (fig. l(e)) and the shape of the lower surface between points G and I was determined in the same manner as the surface shape between points D and G in figure l(c). This process of alternating between the designs of the two Mach number nets with point-spacing adjustments made to match up the expansion lines was continued until the  $l8^{\circ}$  of turning required was obtained. The design was considered correct when the last expansion line from each net met at the same point on the upper surface and the upper and lower surfaces downstream of this last line were parallel and inclined at an angle of  $l8^{\circ}$  with respect to the initial direction of the flow.

As mentioned previously, the method of design involves a process of cutting and trying between each step to obtain agreement between the two nets. A point-by-point correspondence between the two nets is not necessary and small variations in point spacing from one net to the other can be allowed. The difference between the slopes at any pair of corresponding points, however, must remain within the precision to which the net is designed. After the first approximation to the nozzle shape was obtained by the construction of a 2° net for the two Mach numbers, an equivalent 1° net was constructed (fig. 2). In the construction of the 1° net, adjustments in the location of the points of expansion were made, but they were small compared with those found necessary in the initial attempts made with the 2° nets shown in figure 1.

Characteristic nets were then constructed for three intermediate Mach numbers and Mach numbers of 1.6 and 2.8 by using the shape of the lower surface, as determined before, and finding the shape of the upper surface required to give uniform flow in the test section for the Mach number chosen. For a Mach number range between 1.6 and 2.8 the shape of the upper block agreed within the precision of the construction with the shape for the two design Mach numbers of 1.71 and 2.63. Characteristic nets were not constructed for Mach numbers lower than 1.6 because at the lower Mach numbers the nozzle becomes much longer than that required to produce uniform flow with the usual type of nozzle. It was thought, therefore, that the expansion process would be so gradual that fairly uniform velocity would be obtained in the test section.

Since the net for the lower design Mach number 1.71 was constructed so that each expansion wave originating from the lower surface was canceled by suitable curvature of the upper surface, it can be seen that the flow between any two of the characteristic lines of this net can be considered as the flow between two lines in a Prandtl-Meyer expansion

around a corner. The nozzle contour between these two lines then corresponds to two streamlines of the flow around that corner. pair of adjacent characteristic lines will, of course, have its own corner (see fig. 3); however, continuity of the first derivative can be maintained by setting the tangents to the streamlines (nozzle contour) at the beginning of the flow for any one corner (determined by a pair of characteristic lines) the same as the setting at the end of the preceding corner flow. Two corner locations are left undetermined in this process, the corner for the expansion from 0° to 1° (corner 0,1, fig. 3) and the corner for the expansion from 17° to 18°. The corner (0,1) can be determined by plotting the tangent of the nozzle contour for each point between the 10 and 170 points of expansion as a function of the length and fairing the curve to zero and 180 slope, respectively. The point of zero slope will then be point 0 in figure 3. The corner (0,1) can be determined by drawing a vertical line from point 0 until it intersects the line drawn from point 1. The corner for the expansion from 170 to  $18^{\circ}$  can be treated in the same manner. By following this procedure, the entire shape of the nozzle can be calculated.

In the application of this method to the design of nozzles for Mach number ranges much different from that considered in this paper; it may not be possible to follow exactly the procedure presented step by step. In fact, in a later design for a nozzle to cover the range from 2.5 to 5.0, it was found most practical to design a complete net for the higher Mach number and, while the upper surface is kept fixed, work backwards to design a new lower surface for the lower Mach number. The point spacings on the two lower surfaces were then compared and point spacings adjusted until the two curves agreed.

## APPARATUS AND TESTS

The tests on the variable Mach nozzle were made in one of the blow-down jets at the Langley Gas Dynamics Branch. High-pressure air was throttled to the desired stagnation pressure and discharged through the two-dimensional asymmetric nozzle to the atmosphere.

The nozzle consisted of two solid duralumin nozzle blocks with a width of 3 inches and a test-section height of 3 inches. The 3-inch test section was designed to begin at the point where the last line of the 1° net met the upper wall. No second-minimum section was provided (fig. 4). The ordinates for the blocks are given in tables I and II. The coordinate centers for these ordinates are given in the assembly drawing of figure 5. The Mach numbers shown in this figure for each position of the block are the theoretical Mach numbers for which the block was set. No correction was made to the nozzle to allow for the

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boundary-layer-displacement thickness. Previous experience with symmetrical nozzles in this Mach number and Reynolds number range showed that neglecting the boundary layer resulted in a flow in the test section which was uniform within the precision of measurements but at a Mach number slightly less than the theoretical. The sonic and supersonic portions of the nozzle blocks were machined to a tolerance of ±0.001 inch. The tolerance of the subsonic portion was ±0.005 inch.

The Mach number was changed by simple translation of the lower block along a line parallel to the direction of the flow in the test section. The translation necessary to change the block setting for a Mach number of 1.27 to that for 2.75 amounted to 2.17 test-section heights. The dimensions used to set the relative position of the nozzle blocks for a given Mach number are shown in figure 5 and table III. These dimensions are  $h_{\min}$ , h, and the horizontal displacement of the lower nozzle block relative to the upper block d. The dimension h was maintained at a constant value of 3 inches for all Mach numbers.

Aerodynamically, it does not make any difference whether the lower or the upper block is moved. However, for practical testing considerations where a constant test-section position is to be maintained, the lower block has to be moved, while the upper-block position is kept fixed.

In the nozzle tests reported herein, a filler block was necessary to fair the lower block into the settling-chamber aperture. The side walls were bolted rigidly to the nozzle blocks. When the block setting (Mach number) was to be changed, one side wall was removed; the lower block was shifted to the new position and, together with the filler block corresponding to the new position, was doweled and bolted into place between the two walls.

A nozzle (similar to the one described) in which the Mach number is to be changed during the test run and in which aerodynamic tests are to be performed could have the test-section axis horizontal and the entire subsonic geometry fixed for all Mach numbers.

The side walls used in the preliminary survey had windows which permitted the flow to be visualized along most of the supersonic section of the nozzle. The nozzle Mach number and direction surveys presented in this paper were made with solid side walls (without windows) to eliminate any disturbances which might originate at the window—sidewall juncture. The nozzle-block side-wall joint was metal to metal. A circular rod of rubber in a groove located on the block side wall 1/8 inch below the nozzle surface was used for sealing. (See fig. 4.)

The Mach number distribution in the test section was determined by a static-pressure survey in the vertical center plane of the nozzle with a single static-pressure probe (fig. 6). Using a single probe was insurance against the necessity of calibrating each tube of a multitube rake in order to establish the Mach number level in the test section. A multitube rake small enough to fit in the 3- by 3-inch test section was subject to relatively large construction errors and deflections due to air loads during the test. In order to avoid choking at M = 1.27, a smaller probe was used (fig. 7). The static pressure was measured every  $\frac{1}{12}$ h along the test-section center line in the vertical center plane and  $\frac{1}{6}$ h above and below the test-section center line. The Mach number was calculated from the ratio of the settling chamber and local static pressures.

The direction of the flow was measured with a wedge probe (fig. 8) which had a static-pressure orifice on each side of the wedge. Measurements were taken every  $\frac{1}{12}h$  along the tunnel center line. The wedge included angle (20°) was too great for an attached shock at M = 1.25. The method of determining the flow direction from the wedge measurements is outlined in reference 4.

An attempt was made to maintain the same Reynolds number at each Mach number from 1.27 to 2.75. However, since the nozzle was operated without a second minimum, the Reynolds number increased for the higher Mach numbers (see table IV) because high stagnation pressures were required in the tunnel running condition. The equivalent test-section height for a tunnel operating with atmospheric stagnation pressure is included in table IV. The Reynolds number of the table is referred to the test-section height.

# RESULTS AND DISCUSSION

The summary of the results of the Mach number and flow-direction surveys are shown in figures 9 and 10. In these figures, the Mach number and flow direction at the center line are shown in the region of best flow near the end of the nozzle. The region of best flow was found to exist in a region upstream of the designed test-section region. This region (of the same dimensions as the designed test section) was chosen as that which had the least Mach number and flow deviation over the entire Mach number range. The region of best flow was found to be located at a distance 0.75h upstream of the designed test section (fig. 5). (The length of the nozzle from the minimum section to the beginning of the experimental test section for a Mach number of 2.75 was 4.87 test-section heights.) The displacement of the usable test region

is believed partially due to the existence of a boundary layer on the nozzle surfaces for which no correction was made and possibly due to the conditions existing at the end of the test section. The ambient pressure at the end of the test section was atmospheric, while the pressure of the jet at this point was below atmospheric pressure. Under these conditions it is possible for the boundary layer to separate upstream of the end of the test section and cause irregularities to occur in the flow at this point. With a closed tunnel it may be possible to extend the test region downstream. Except for the lowest test Mach number, the measured Mach number in the test section was less than the design Mach number for all Mach number settings. This condition is also probably due to the existence of the boundary layer.

The complete results of the tunnel calibrations are shown in figure 11. In this figure the test section for which good flow was found is indicated by solid vertical lines and the corresponding test rhombus by dashed lines. A compilation of the nozzle calibration results is given in table V where the Mach number and flow deviations are shown for all Mach numbers. It is possible, owing to the relatively large size of the wedge probe, that any concentrated disturbances striking the wedge ahead of the orifice would give twice the value of the actual variation in pressure existing at that point because of its reflection on one surface of the wedge and thus affect the flow-angle measurements.

The results of the Mach number survey for a Mach number of 1.25 cannot be analyzed in the same manner as the results for the other Mach numbers, because, when the probe was in the  $\frac{1}{6}$ h position off the center line, the shock from the cone apex was reflected from the nozzle surface back onto the probe at a position very close to the static orifices. These readings, however, can be used to determine the variation in Mach number along each of the three longitudinal lines along which the survey was made. In table V it will be seen that the measured Mach number 1.27 was greater than the Mach number for which the block was set. For this case, the blocks were moved so far off the lower design condition that the sonic line cannot be assumed to be straight. When the blocks were set with the same criteria used to set the other block positions there was a section downstream of the position of the first minimum which had a cross-stream dimension slightly less than the  $h_{\min}$  value used to set the nozzle blocks. A higher test-section Mach number than expected can be justified from these considerations.

The accuracy of measuring the Mach number and flow direction was determined from the scatter of test points obtained from several tests made under the same conditions. The accuracy of the flow direction was  $\pm 0.10^{\circ}$  and the accuracy of the Mach number measurement was  $\pm 0.01$ .

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Typical schlieren photographs taken during the preliminary runs are shown in figure 12 for Mach numbers of 1.54, 1.87, and 2.75. It can be seen that no large disturbances exist in the flow. The multitube rake shown in the photographs was that used in the preliminary surveys.

# CONCLUSIONS

A method of designing an asymmetric, fixed-geometry, variable Mach number nozzle has been developed by using the method of characteristics. A small nozzle conforming to the analytically determined ordinates was constructed and calibrated over a range of Mach numbers extending from 1.27 to 2.75. The results show the variation in Mach number to be  $\pm 0.02$  or less and in the flow direction to be  $\pm 0.2^{\circ}$  within the test section. The range of Mach numbers from 1.27 to 2.75 was obtained by translating the lower block in a straight line parallel to the test-section center line for a distance of 2.17 test-section heights.

The length of the nozzle from the minimum section to the beginning of the experimental test section for M=2.75 was 4.87 test-section heights.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., April 19, 1951.

### REFERENCES

- 1. Allen, H. Julian: The Asymmetric Adjustable Supersonic Nozzle for Wind-Tunnel Application. NACA TN 2919, 1953. (Supersedes NACA RM A8E17.)
- 2. Görtler, H.: Zum Übergang von Unterschall- zu Überschallgeschwindigkeiten in Düsen. Z.f.a.M.M., Bd. 19, Heft 6, Dec. 1939, pp. 325-337.
- 3. Ferri, Antonio: Completed Tabulation in the United States of Tests of 24 Airfoils at High Mach Numbers (Derived from Interrupted Work at Guidonia, Italy, in the 1.31- by 1.74-Foot High-Speed Tunnel). NACA ACR L5E21, 1945.
- 4. Ferri, Antonio: Elements of Aerodynamics of Supersonic Flows.
  The Macmillan Co., 1949.

TABLE I

VARIABLE MACH NUMBER NOZZLE - UPPER BLOCK ORDINATES

x <sub>U</sub> , in.	y <sub>U</sub> , in.	x <sub>U</sub> , in.	y <sub>U</sub> , in.	x <sub>U</sub> , in.	$y_U$ , in.	x <sub>U</sub> , in.	$y_U^{}$ , in.
1.039 1.125 1.250 1.375 1.500 1.625 1.750 1.625 1.750 2.250 2.375 2.500 2.625 2.750 2.625 2.750 2.625 2.750 3.625 3.750 3.625 3.750 3.625 4.250 4.375 4.625 4.750 4.625 4.750 5.375 5.500 5.375 5.500 5.625 5.750 5.625 6.500 6.625	9.760 9.732 9.692 9.651 9.610 9.570 9.529 9.489 9.448 9.367 9.326 9.245 9.164 9.001 8.961 8.921 8.800 8.721 8.800 8.721 8.681 8.642 8.655 8.490 8.453 8.407 8.379	6.750 6.875 7.000 7.125 7.250 7.375 7.500 7.625 7.750 8.000 8.125 8.250 8.375 8.500 8.625 8.750 8.875 9.000 9.125 9.250 9.375 9.500 9.625 9.750 9.875 10.000 10.125 10.250 10.375 10.500 10.625 10.750 10.625 11.750 11.625 11.750 11.625 11.750 11.875 11.500 11.125 11.250 11.375 11.500 11.625 11.750 11.875 12.250	7.999 7.967 7.935 7.903 7.872 7.840 7.810 7.750 7.691 7.662 7.633 7.605 7.523 7.496 7.470 7.444 7.419 7.394 7.369 7.345 7.298 7.321 7.298 7.325 7.252 7.230 7.208 7.166 7.166 7.166 7.166 7.069 7.051 7.069 7.070 7.087 7.069 7.070 7.087 7.087 7.087 7.087 7.087 7.087 7.087 7.087 7.098 6.984 6.940	12.375 12.500 12.625 12.750 12.875 13.000 13.125 13.250 13.375 13.500 13.625 13.750 13.875 14.000 14.125 14.250 14.375 14.500 14.625 14.750 14.875 15.250 15.375 15.500 15.625 15.750 15.625 15.750 16.625 21.625 21.750 22.250 22.375 22.250 22.750	6.926 6.913 6.900 6.889 6.877 6.867 6.857 6.857 6.857 6.831 6.824 6.811 6.805 6.792 6.789 6.789 6.785 6.785 6.778 6.777 6.776 6.7776 6.7776 6.7776 6.7776 6.7770	22.875 23.000 23.125 23.250 23.375 23.500 23.625 23.750 23.875 24.000 24.125 24.250 24.375 24.625 25.375 25.625 26.375 26.625 27.375 26.625 27.375 28.375 28.375 28.375 28.375 28.375 29.375	6.768 6.765 6.762 6.756 6.756 6.756 6.733 6.6723 6.6723 6.6723 6.6723 6.6724 6.6723 6.6724 6.6723 6.6724 6.6723 6.6724 6.6723 6.6724 6.6723 6.6724 6.7724 6.7724 6.7724 7.

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TABLE II

VARIABLE MACH NUMBER NOZZLE - LOWER BLOCK ORDINATES

		П		11	
x <sub>L</sub> , in.	y <sub>L</sub> , in.	x <sub>L</sub> , in.	$y_L$ , in.	x <sub>L</sub> , in.	$y_L$ , in.
0 .625 .875 1.625 1.875 1.625 1.875 2.125 2.375 2.625 3.125 3.625 4.375 4.625 4.375 4.625 5.375 5.625 7.125 6.625 7.125 7.875 8.375 8.375 8.375 7.625 7.875 7.875 8.375 9.375 9.375 10.375 10.375 10.375 11.375 11.375 11.625	5.055 5.177 5.258 5.340 5.583 5.583 5.5846 5.583 5.5846 5.589 6.314 6.395 6.314 6.395 6.801 6.801 6.801 6.801 6.801 7.207 7.288 7.451 7.532 7.613 7.7538 8.019 8.100 8.182 8.344 8.425 8.587 8.688 8.750 8.831	11.875 11.976 12.125 12.250 12.375 12.500 12.625 12.750 12.875 13.000 13.125 13.250 13.375 13.500 13.625 13.750 13.875 14.000 14.125 14.250 14.375 14.500 14.625 14.750 15.250 15.375 15.000 15.125 15.250 15.375 16.000 16.125 16.250 16.375 16.500 16.875 17.000 17.125 17.250 17.375 17.500	8.912 8.945 8.993 9.032 9.071 9.109 9.147 9.185 9.223 9.260 9.296 9.332 9.403 9.437 9.570 9.537 9.570 9.666 9.729 9.760 9.789 9.760 9.789 9.760 9.789 9.952 9.978 10.026 10.049 10.072 10.094 10.115 10.136 10.157 10.197 10.215 10.232 10.248	17.625 17.750 17.875 18.000 18.125 18.250 18.375 18.500 18.625 18.750 18.875 19.000 19.125 19.250 19.375 19.500 19.625 19.750 19.875 21.375 21.625 22.375 22.125 22.375 23.375 23.375 23.625 24.125 24.375 24.625 24.875 24.625 24.875 25.125 24.875 25.125 26.625 27.375 26.625 27.375 26.625 27.375 27.625 27.720	10.264 10.279 10.294 10.308 10.320 10.329 10.337 10.343 10.359 10.360 10.361 10.365 10.365 10.365 10.365 10.359 10.358 10.359 10.351 10.359 10.351 10.359 10.351 10.359 10.355 10.365 10.365 10.365 10.365 10.365 10.365 10.365 10.365 10.37 10.359 10.

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TABLE III

POSITIONING DIMENSIONS FOR NOZZLE BLOCKS

Theoretical Mach number	h <sub>min</sub> /h	d/h
1.25 1.60 1.71 1.90 2.20 2.63 2.80	0.96 .80 .74 .64 .50 .34	1.73 1.26 1.07 .77 .33 17

TABLE IV
TEST REYNOLDS NUMBERS

Measured Mach number	Test Reynolds number	Equivalent test- section height for atmospheric stagnation pressure, ft
1.27 1.54 1.66 1.87 2.15 2.57 2.75	5.25 × 10 <sup>6</sup> 5.39 5.54 5.16 5.47 6.32 6.13	1.185 1.270 1.355 1.355 1.610 2.290 2.460

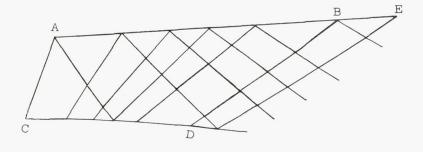


TABLE V

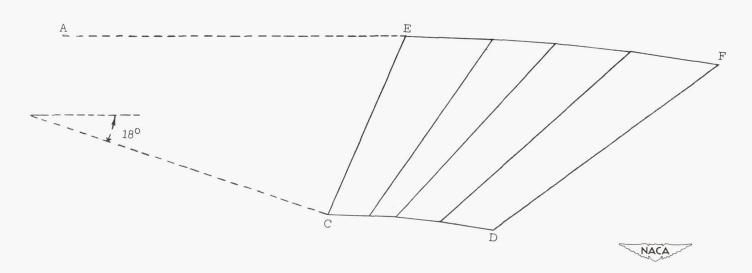
SUMMARY OF NOZZLE-CALIBRATION RESULTS

Theoretical Mach number	Measured Mach number	Mach number variation, experimentally determined test region	Mach number variation, test rhombus	Flow-direction variation, test-region center line, deg	Flow-direction variation, test-rhombus center line, deg
1.25	1.27	±0.020	±0.020		
1.60	1.54	±.015	±.015	±0.18	±0.25
1.71	1.66	±.015	±.015	±.17	±.17
1.90	1.87	±.010	±.010	±.22	±.37
2.20	2.15	±.020	±.020	±.15	±.23
2.63	2.57	±.010	±.015	±.11	±.17
2.80	2.75	±.017	±.025	±.08	±.235



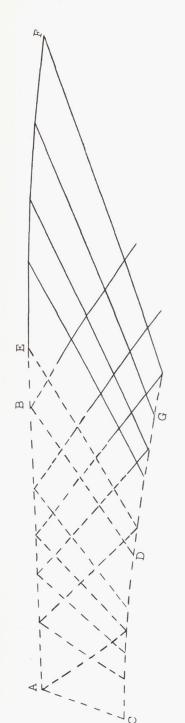


(a) M = 2.63.

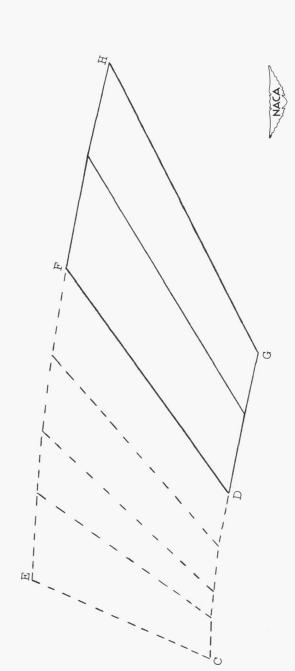


(b) M = 1.71.

Figure 1.- The  $2^{\circ}$  characteristic-net construction.



(c) M = 2.63.



(d) M = 1.71.

Figure 1.- Continued.

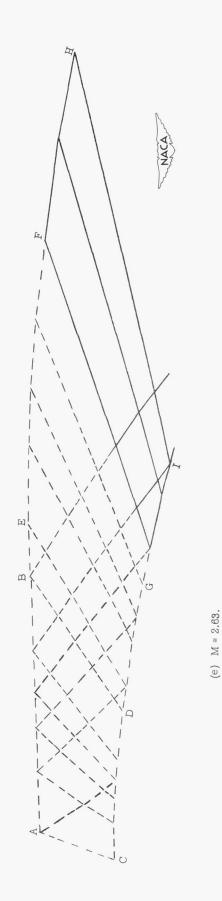
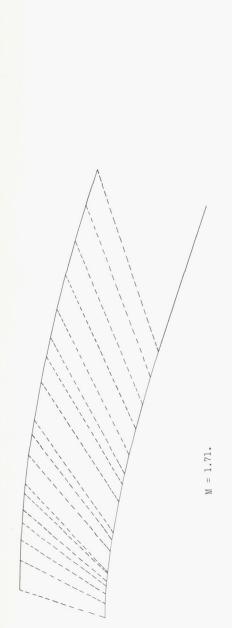


Figure 1.- Concluded.



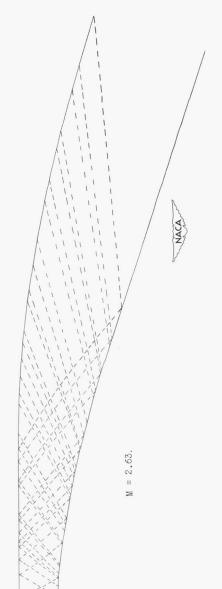


Figure 2.- The  $1^{\rm O}$  characteristic-net construction.

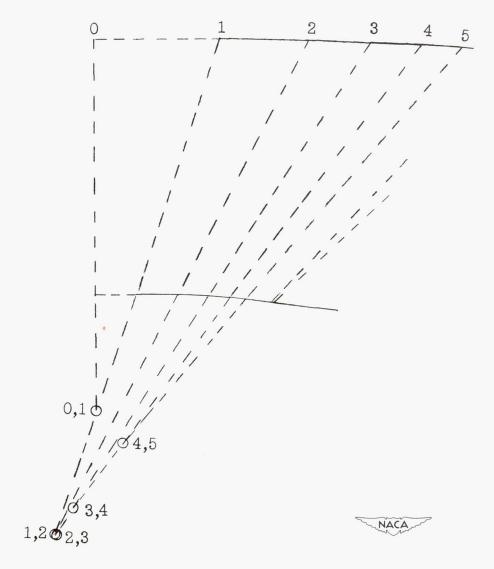


Figure 3.- Corner-flow construction. M = 1.71.

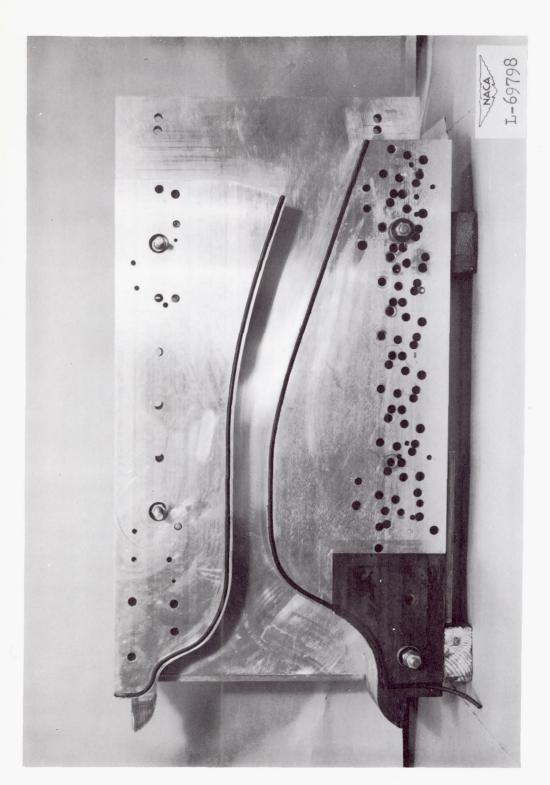


Figure 4.- Photograph of nozzle assembly.

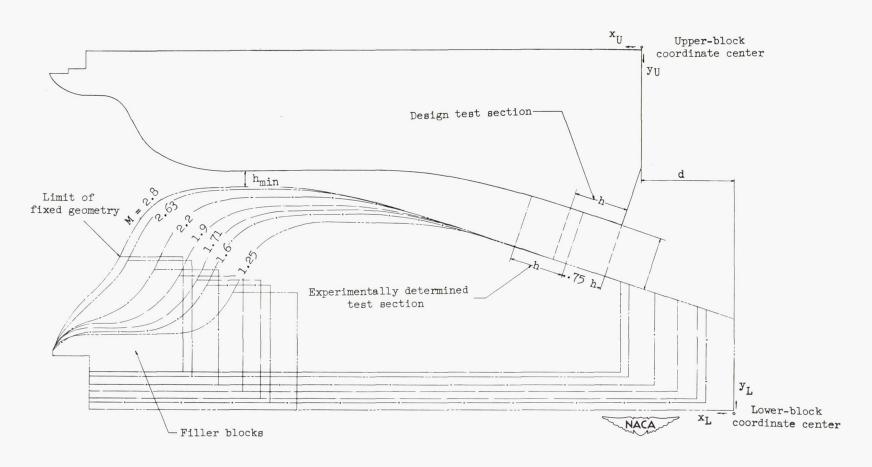


Figure 5.- Assembly drawing of nozzle blocks. (Mach numbers indicated are the theoretical Mach numbers for which the block was set.)

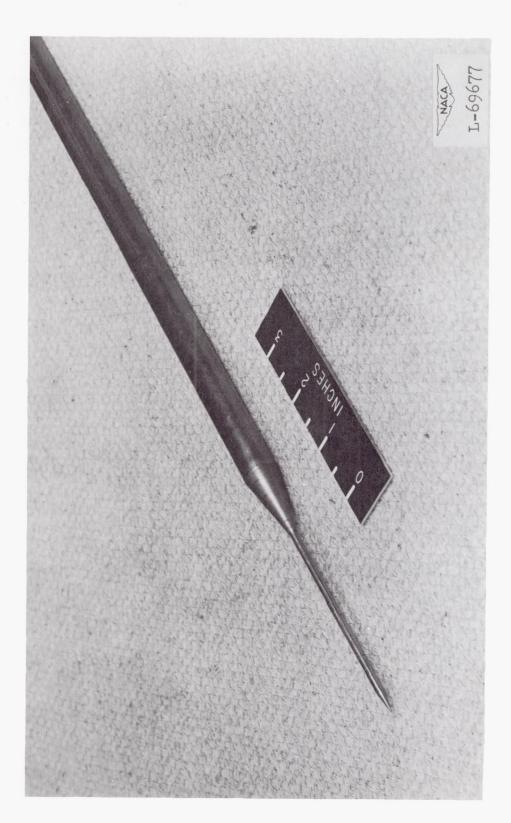


Figure 6.- Static-pressure probe.

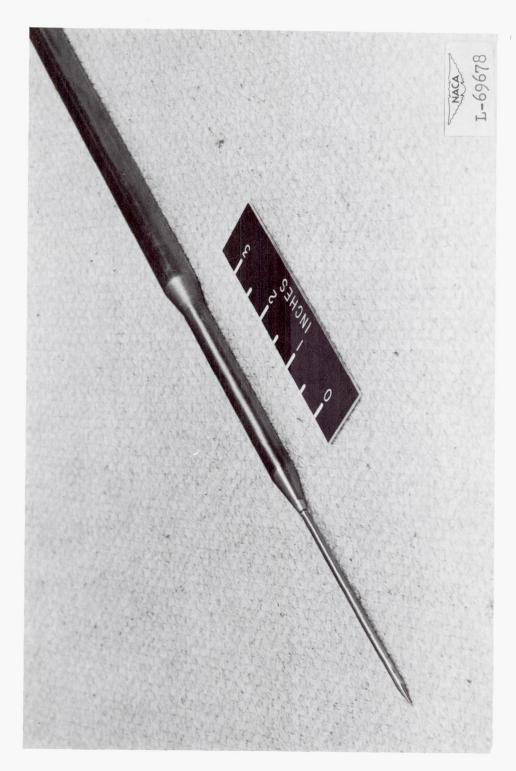
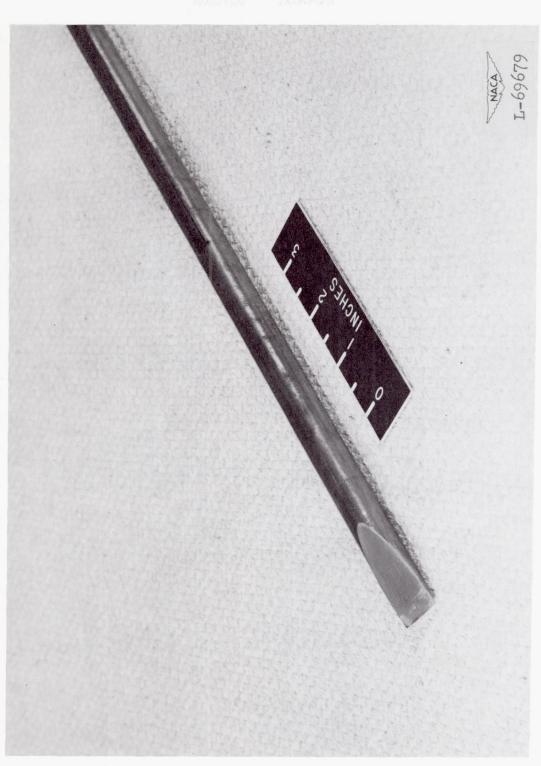


Figure 7.- Static-pressure probe used at M = 1.27.



Figure 8.- Wedge probe.



Average measured Mach number

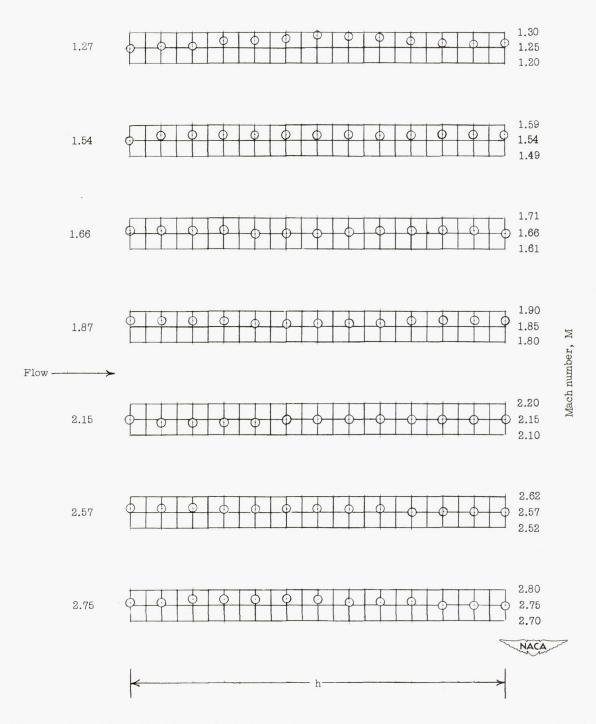


Figure 9.- Distribution of Mach number M along the tunnel center line in the experimentally determined test section.

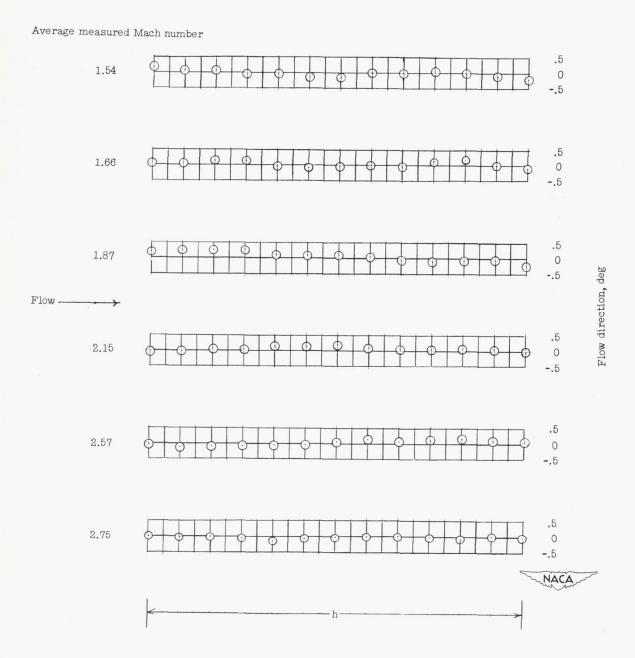


Figure 10.- Variation of the flow direction along the tunnel center line in the experimentally determined test section.

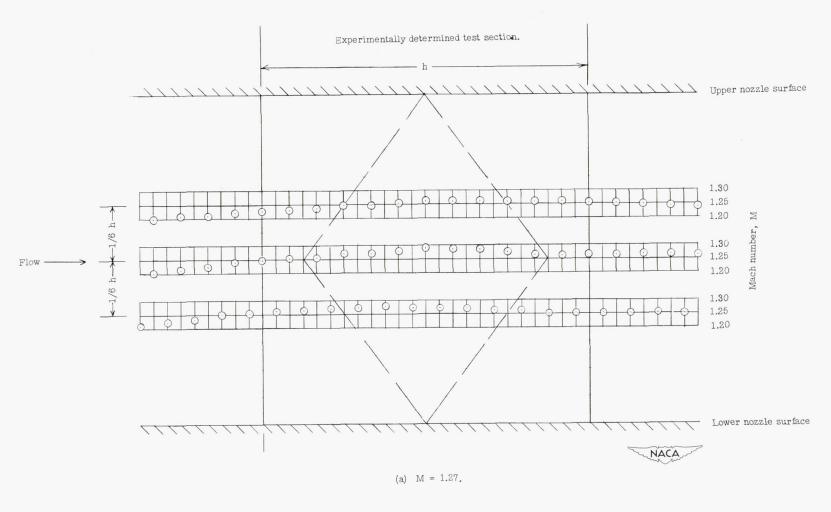


Figure 11.- Complete calibration results.

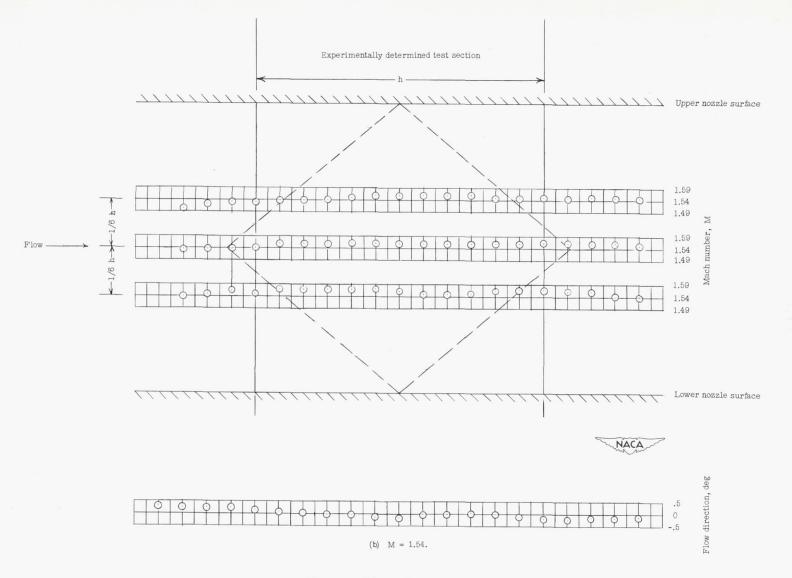


Figure 11.- Continued.

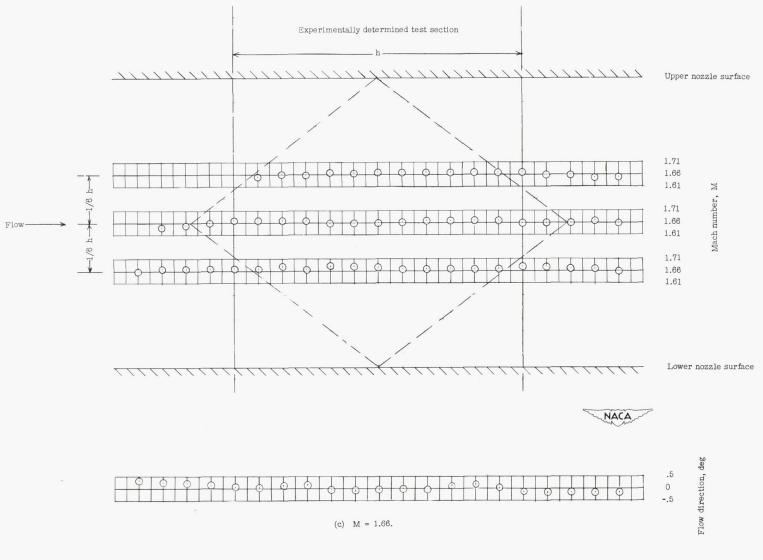


Figure 11. - Continued.

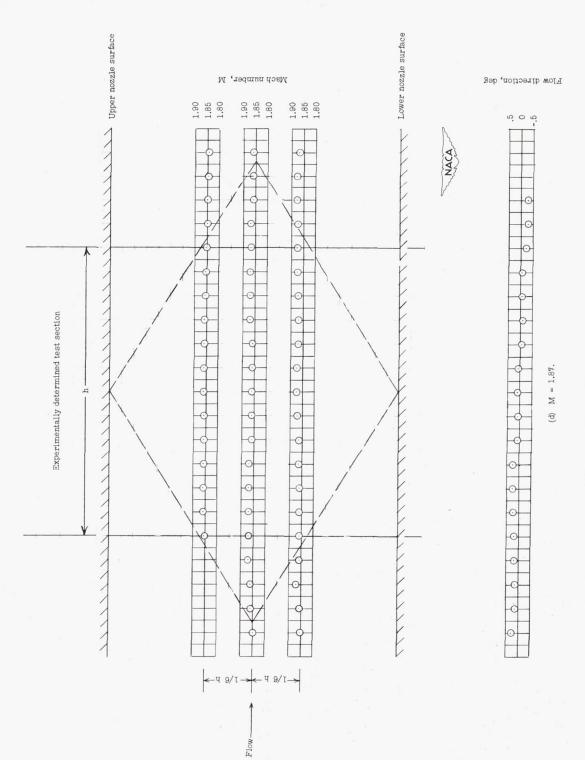


Figure 11.- Continued.

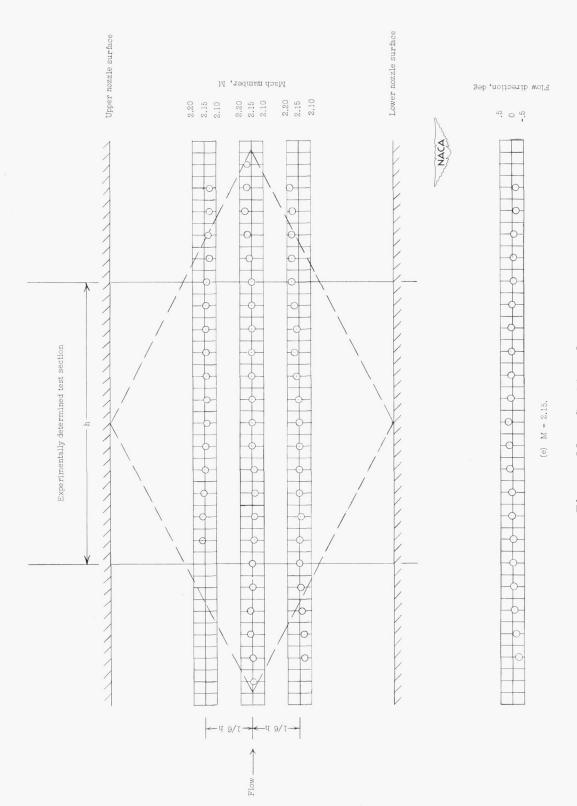


Figure 11.- Continued.

H

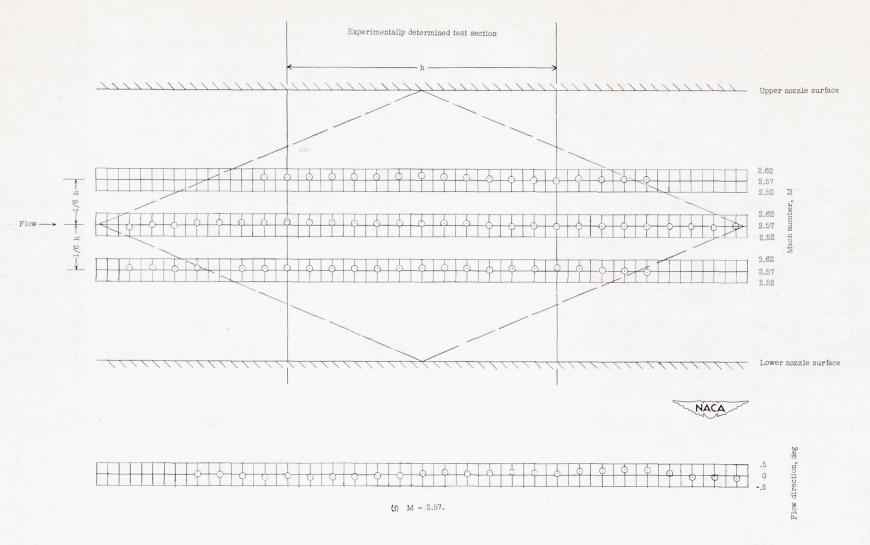


Figure 11. - Continued.

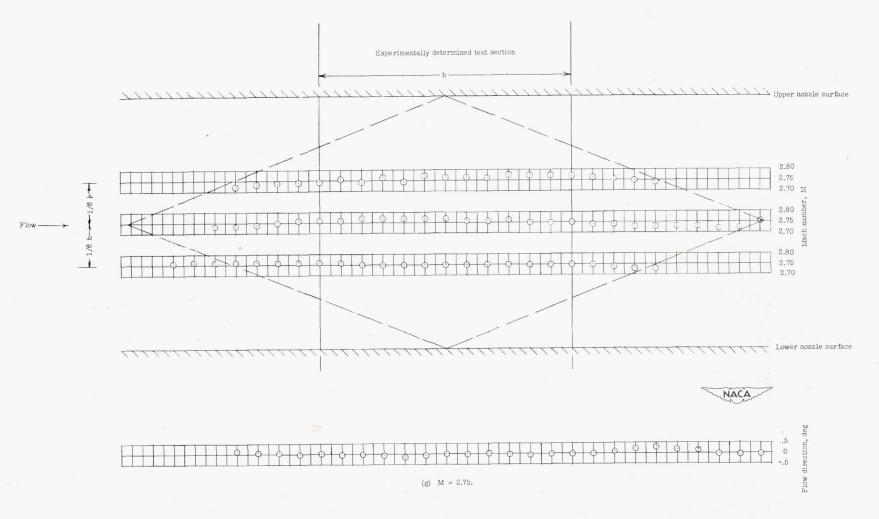
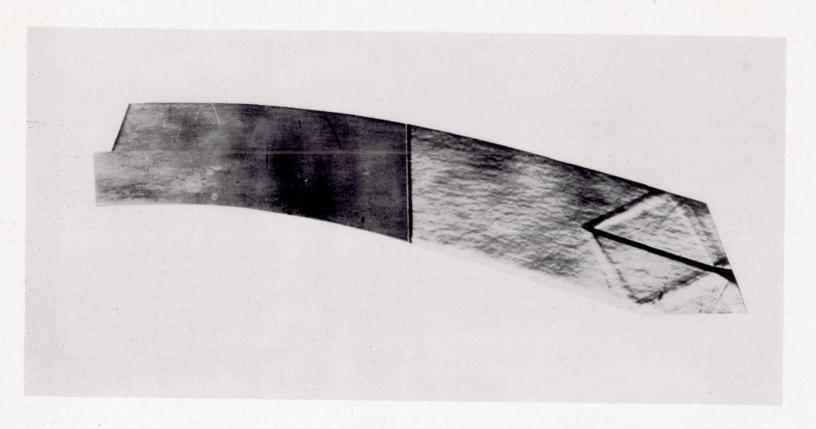


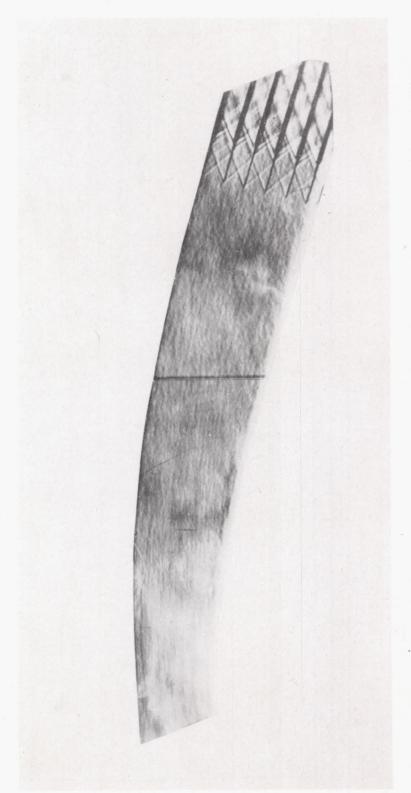
Figure 11. - Concluded.



(a) M = 1.54.

L-69130

Figure 12.- Schlieren photograph of flow in the nozzle.

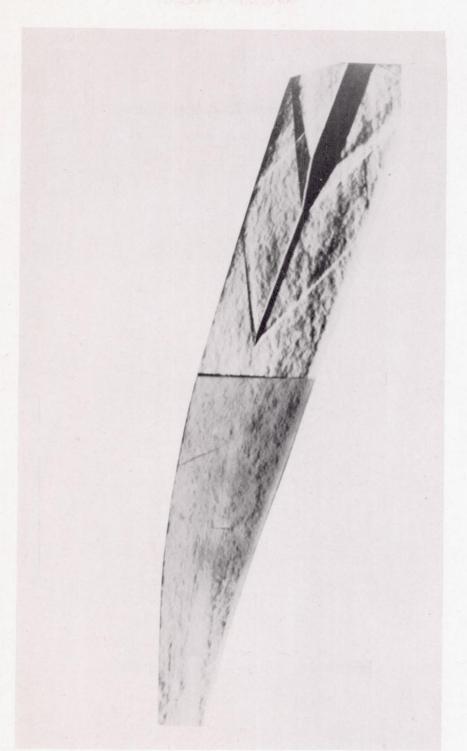


L-69131

(b) M = 1.87.

Figure 12. - Continued.





(c) M = 2.75.

Figure 12. - Concluded.